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Ten-year storability and field efficacy of the biopesticide *Metarhizium acridum* in desert locust management

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Abstract

The fungus *Metarhizium acridum* (Driver & Milner) (Hypocreales, Clavicipitaceae) is the most effective alternative to conventional insecticides for controlling the desert locust, *Schistocerca gregaria* (Forskål, 1775) (Orthoptera; Acrididae). Demonstrating its storability and efficacy under variable field conditions is essential for promoting the systematic implementation of biological control in desert locust management, but little information is available. In 2014, the Mauritanian National Desert Locust Centre received a fungus powder formulation (Green Muscle) from FAO/CLCPRO. Spore viability was monitored for 10 years while the product was kept in a refrigerator at 4 °C. For the field efficacy assessment, seven 20-ha plots were treated with the formulation. The formulation was transported, used, and stored in the field without storage facilities. Applications were conducted using a hand-held sprayer with a dose rate of 50 g in 2 L gasoil per hectare. Two of the seven plots were selected to investigate the influence of host plant (*Schouwia thebaica*) size and cover on efficacy. Plot A had large, widely spaced plants, and Plot B had small, closely spaced plants. Spore viability and virulence remained unaffected after 10 years of storage. Field application of the biopesticide reduced the locust population by more than 80% within two weeks. Plant size and cover had no significant effect on biopesticide efficacy. Mortality of caged nymphs from Plot A was 82.8% and from Plot B was 83.9% compared to 4.3% in the untreated control. These results demonstrate the remarkable storability and field efficacy of *M. acridum* and support its integration into desert locust management programs.

Keywords

Biological control, biopesticide, field efficacy, *Metarhizium acridum*, *Schistocerca gregaria*, spore viability, vegetation structure

Introduction

The desert locust, *Schistocerca gregaria* (Forskål, 1775) (Orthoptera; Acrididae), is a major transboundary pest in arid and semi-arid areas from North Africa to the Indo-Pakistan borders, with approximately 60 countries at risk during plague periods (FAO 2024). Control has relied heavily on organophosphate insecticides such as chlorpyrifos, which are inexpensive and fast-acting but increasingly restricted due to environmental and human health concerns (FAO 2021).

Biological control using the entomopathogenic fungus *Metarhizium acridum* (Driver & Milner) (Hypocreales; Clavicipitaceae) has been recommended as part of integrated locust management since its development (Lomer et al. 2001, FAO 2021, Word Ries et al. 2024, Yasin et al. 2024). Field trials have demonstrated its effectiveness against early-stage nymph bands. During the 2020–2021 Horn of Africa outbreak, it was successfully applied to several hundred thousand hectares (Owuor and David McRae 2022), achieving > 80% mortality within two weeks (Mullié et al. 2023). Two commercial formulations—Green Muscle (*M. acridum*, strain IMI330189) and Novacrid (*M. acridum*, strain EVCH077)—are currently available.

Operational use of *M. acridum* faces two main challenges: maintaining spore viability during storage in remote field conditions, and ensuring efficacy under variable environmental factors such as temperature (Blanford and Klass 2004, Van der Valk 2007) and vegetation structure (Van der Valk 2007, Aw and Hue 2017). Vegetation can enhance efficacy by protecting spores from solar radiation and increasing contact with locusts, although the influence of plant size and cover under operational conditions remains unclear (Atheimine et al. 2014).

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Few studies have assessed the long-term storage stability of *M. acridum* formulations or their field efficacy after extended storage with consideration of the varying conditions encountered during desert locust control (Word Ries et al. 2024). This study was conducted as part of a desert locust control campaign by a "Green Team" introduced by the Mauritanian National Desert Locust Control Center. Biological treatment was conducted against several nymph bands and locust groups located in the winter breeding zone in northern Mauritania using a powder formulation of *M. acridum* (Green Muscle).

This study aimed to provide evidence of the potential use of *M. acridum* in desert locust management under field conditions. To the best of our knowledge, no previous study has been published regarding the long-term monitoring (10 years) of stored biopesticide formulations. Specifically, we evaluated (1) spore viability after long-term refrigerated storage and (2) field efficacy in relation to plant size and cover.

Materials and Methods

Viability of the spores.—The storability and efficacy of a batch of 50 bags of 1 kg each of a powder formulation of Green Muscle biopesticide, *Metarhizium acridum* (strain IMI330189), which was stored in a refrigerator (set at 4 °C) at the Mauritanian National Desert Locust Control Centre in August 2014, were evaluated. According to the product label, each gram of the formulation contains 5 x 10^{10} spores. Although the water content was not specified, it is commonly ≤ 5% for the powder formulation.

The viability of the spores in the stored formulation was evaluated using germination tests. Tests were conducted on samples (a bag of 1 kg) taken from the batch of the formulation every one to two years. Furthermore, the viability of the spores was monitored for a sample that was removed from the refrigerator after two years and then kept under unrefrigerated conditions in a room for one year.

In the framework of a locust control operation, a bag of 1 kg taken from the fridge in March 2016 was used for field application over five days (reported in this study). During this five-day period, the biopesticide was in the field under ambient temperatures. After treatments, 5–10 g of the remaining formulation in the bag was placed under tree shade, and spore viability was assessed after one month.

Germination tests were conducted under laboratory conditions using two Petri dishes with Extramalt or Sabouraud's medium according to (Lutte Biologique contre les Locustes et les Saute´riaux (LUBILOSA) 1999, Ould Etheimine et al. 2013). This involved inoculating the Petri dishes with 0.1–0.2 mL spore solution at a concentration of 10^3 to 10^4 spores/mL and incubation at 28 °C ± 2 °C for 18–20 h. Viable spores (germinated spores) were observed under a microscope at × 400 magnification.

To facilitate spore counting, an appropriate suspension of spores for germination tests (typically 10^3–10^4 spores/mL) was observed after successive ten times dilutions using gasoil. To prepare a stock solution of 5 × 10^9 spores/mL based on the concentration of spores on the package, 1 g of the formulation was dissolved in 10 mL of gasoil. The stock solution was used for successive ten times dilutions until an appropriate spore suspension was obtained. Each dilution was used to prepare the next by mixing 1 mL of the dilution with 9 mL of gasoil. Each dilution was agitated for several seconds in a Vortex Genie 2 electric mixer (Bender and Hobein AG, Zurich, Switzerland).

After an incubation period of 18–20 h, a minimum of 300 germinated and non-germinated spores were counted. Counting was repeated three times, and the mean was used to calculate the percentage of germinated spores (viability) using the following formula: Viability (%) = (germinated spores/germinated spores + non-germinated spores) × 100).

Virulence of the spores.—The monitoring period for stored formulations was fixed at 10 years. After confirming spore viability, it was essential to assess their virulence in locusts. Bioassays were conducted to ensure that, even with a good germination rate in culture medium, the fungal spores maintained their virulence against locusts. We planned to examine the spores' virulence and viability simultaneously, but the founding insects for the bioassay were not consistently detectable. Consequently, bioassays were conducted at the reception of the formulation batch, after five years, and after ten years of storage using locust nymphs collected from the field.

In all bioassays, a single dose of 5 × 10^4 spores/locust was applied using a volume of 1 µL/insect. This dose was obtained after two ten times dilutions, as described above, representing 5 × 10^7 spores/mL. For the final bioassay, using spore stored for 10 years, an additional low dose of 5 × 10^1 spores/locust (dilution with 5 × 10^4 spores/mL) was used to further examine virulence.

A drop of the spore suspension (1 µL) was directly deposited onto the locusts using a micro-applicator (Burkard SA Co., UK). Three replicates of 20 desert locust nymphs of L4 stages collected from the field were used. The same number of nymphs was used as a control. In all cases, the nymphs were monitored in aluminum cages with dimensions of 50 × 50 × 50 cm.

Field efficacy of the formulation.—Field efficacy of the biopesticide was evaluated using a sample of the batch taken from the refrigerator after three years of storage. This part of the study aimed not only to demonstrate the efficacy of the biopesticide under field conditions but also to investigate the potential influence of vegetation structure on its performance. Because of the high density and homogeneity of vegetation in the study area, efficacy was assessed in relation to plant size and cover. The vegetation was mainly dominated by *Schouwia thebaica* at more than 90%. *Limeum viscosum, Neurada procumbens, Heliotropium ramosissium, Fagonia oliveri, and Lotus Spp* dominated the low vegetation stratum. Vegetation density was classified as low, medium, or high based on green coverage compared to bare ground (FAO 2001).

Study area.—For field use, the study was conducted as part of a desert locust control campaign by a "Green Team," which focused on biopesticide applications. The intervention zone was located in a desert locust breeding area in northern Mauritania 70 km to the north of Zouérat, the capital town of Willay of Tiris Zemmour (23 °14'N, 12 °17'W). This zone is characterized by multiple wadies of *Schouwia thebaica* plants. Because of the high density of this plant species, the local population was named Waïd Jerjir (in the local language), which means wadi of *Schouwia*.

The study area was approximately 500 ha in which several dispersed nymph bands had been identified. The treated area was divided into seven plots, totaling 20 ha (2–3 ha each), based on the presence of nymph bands. The plots were sufficiently separated, approximately two to three kilometers apart, and had comparable climatic and ecological conditions. Far from the treated area, at approximately ten kilometers, the control zone (23 °17'14"N, 12 °11'15"W) was identified to have a comparable biotope and infestation. We counted at least five plots with nymph bands in the control area.

Biopesticide application.—Applications were carried out in the early morning (09:00–11:00) and again in the late afternoon

(16:00–18:00) for five consecutive days. Treatments were conducted using a hand-held sprayer (Ulva+) at a recommended dose of 50 g/ha (2.5 x 10^{12} spores/ha). The formulation was mixed with gasoil, and the sprayer was calibrated to deliver 2 L/ha using a blocked nozzle with a 10 m track spacing. Temperature, humidity, and wind speed were recorded during the biopesticide application. Temperature and humidity were recorded during the monitoring period.

A total of seven plots containing small hopper bands, predominantly at the L3 and L4 instar stages, were treated. The size of these hopper bands ranged from 3,000 to 5,000 m^2. Meteorological conditions, measured 1.5 m above the ground during the biopesticide application, showed temperatures ranging from 23 to 26 °C, relative humidity from 34 to 48%, and wind speed from 3 to 5 m^{-1}.

During biopesticide application, the total applied volume for each plot was prepared in a separate container (the capacity of the pulverization tank was 1 L). Two sprayers were used for each plot. Once the tank from the first application was empty, the treatment was continued with the second applicator, which had already been prepared, until the entire area of the plots was covered.

Field observations.—To characterize the plant size and cover in the treated plots, the length (L), width (W), and height (H) of the sampled plants of *S. thebaica*, which largely dominated the study area, were measured in two plots: Plot A (23°15'55"N, 12°18'42"W) and Plot B (23°14'05"N, 12°18'10"W). The plots were of three hectares each and chosen to have a clear difference in vegetation structure. Plant size and cover were measured in each plot. Vegetation density was classified as low or high according to green coverage in comparison to bare ground (FAO 2001). These plots also served as sampling sites, and the collected insects were subsequently caged for observations.

Plant size was calculated [Size (m^3) = L (m) × W (m) × H (m)] according to a previously published study (Ould Maeno et al. 2012). The distance between the plants was also measured. The sampled plants were randomly selected at several points and fixed along the treated plots by traversing the plots from side to side. All measurements were performed by the same person using a steel measuring tape.

Field observations focused on locust behavior and density following biopesticide application. Detailed observations were made before treatment, after one week, and after two weeks (end of observation) in plots A and B. These observations considered the complexity and density of nymph bands. For cage monitoring, nymph samples were collected from Plots A and B two days after biopesticide application.

Locust density in the field was estimated by band size (length × width) during periods of activity. In the treated plots, the rapid dispersal of nymph bands did not allow for a reliable estimate of the changes in band density or size. Field evaluation was therefore limited to qualitative observations. The size of the bands was measured only before biopesticide application to characterize the initial infestation. Biopesticide effectiveness was mainly assessed using caged insects. At the end of the observation period, intensive surveys using a pick-up vehicle were conducted to evaluate the locust populations in both treated and untreated zones (FAO 2001).

Caging insects.—In total, 150 nymphs of L3 and L4 stages were randomly collected from different parts of each plot in the early morning two days after biopesticide application. Nymphs were hand-collected using an insect net. To avoid cross-contamination, nymphs were collected by two people: one for Plot A and one for Plot B. An equal number of nymphs were collected from the untreated zone as a control.

Three mesh cages were prepared. Each cage contained 50 nymphs, corresponding to the three treatments: Control, Plot A, and Plot B. Nymphs were fed with uncontaminated vegetation collected from the untreated zone. The cages were placed in the study area under non-dense shade of trees to protect nymphs from direct sunlight during the hottest part of the day. Mortality was recorded daily over a two-week period.

Statistical analysis.—The mortality rates and all measures of vegetation are expressed as mean ± standard deviation. Data were analyzed using IBM SPSS Statistics version 27. Field efficacy was measured by the mortality rate (%) of caged nymphs in the treated zone (Plot A and Plot B) and untreated zone (Control). Mortality rate was subjected to logarithmic transformation (log10) to stabilize the variance. Data were analyzed using a one-way ANOVA to compare the Control with Plot A and Plot B. When significant differences were detected (i.e., $p < 0.05$), a post-hoc Student-Newman-Keuls (SNK) test was performed to identify distinct mean groups and clarify the relative effects of the biopesticide in Plot A and Plot B.

Mean plant dimensions [length (m), width (m), and height (m)] and size (m^3) (length x width x height) and the distance between plants (m) were compared between Plots A and Plot B using a non-parametric test (Mann-Whitney U test), given that the data did not conform to the assumption of normality required for parametric analyses. The differences were considered statistically significant at the $p < 0.05$ level.

Results

Spore viability.—No loss of spore viability was observed in the powder formulation of *M. acridum* stored at 4 °C for 10 years. Spore viability remained consistently high (> 90%) in all samples tested every one to two years, with no significant difference from the initial germination rate at reception. Details are presented in Table 1.

A 1-kg bag removed from refrigeration after three years was used for field application. The viability of the spores was checked for the formulation residues after one month. This sample had been transported for three days and used for treatments over a five-day period without refrigeration, yet viability remained at 97.53 ± 1.43% (Table 1: 4th sampling order), which is not significantly different from the other viability tests shown in Table 1. Similarly, a second 1-kg bag removed from refrigeration after two years and

Table 1. The viability of the spores in samples taken from *Metarhizium acridum* over the course of ten years of refrigerated storage (refrigerator set at 4 °C). No significant variation of viability rate during the all-storage period (F = 2.414; df = 7, 16; $p = 0.068$).

Sampling order	Sampling year	Storage period	Storage conditions	Viability (%) ± SD
1st	2014	Reception	Refrigerator	98.31 ± 0.46
2nd	2015	1 year	Refrigerator	97.84 ± 0.54
3rd	2016	2 years	Refrigerator	93.32 ± 1.87
4th	2016	2 years	2 years (refrigerator) + 1 month (field: 23.01 °C ± 5.67)	97.53 ± 1.43
5th	2017	3 years	Refrigerator	93.42 ± 0.48
6th	2017	3 years	2 years (refrigerator) + 1 year (room: 30.91 °C ± 7.22)	96.03 ± 1.97
7th	2019	5 years	Refrigerator	97.93 ± 1.41
8th	2021	7 years	Refrigerator	92.41 ± 0.38
9th	2023	9 years	Refrigerator	94.78 ± 2.58
10th	2024	10 years	Refrigerator	96.53 ± 1.19

The refrigerator was set at 4 °C, and power outages were recurrent. Malt extract was used for the tests conducted at reception and for the 1st and the 2nd samples, while Sabouraud medium was used for the subsequent tests.

stored at ambient temperature for one year maintained a viability rate of 96.03 ± 1.97% (Table 1: 6th sampling order).

Spore virulence was confirmed in laboratory bioassays conducted at reception (Fig. 1), 5 years of storage (Fig. 2), and 10 years of storage (Fig. 3). At a dose of 5×10^4 spores/nymph (dilution factor of 1:1000), the mortality of the treated locust nymphs was recorded daily over the two weeks post-application.

To further confirm the viability and virulence of spores after 10 years of storage, locust nymphs were treated with a very low dose of the biopesticide (5×10^1 spores/nymphs locust; representing a dilution factor of 1:1000000). While the results of this treatment showed a delay, the total mortality was comparable to that of the high dose (Fig. 3).

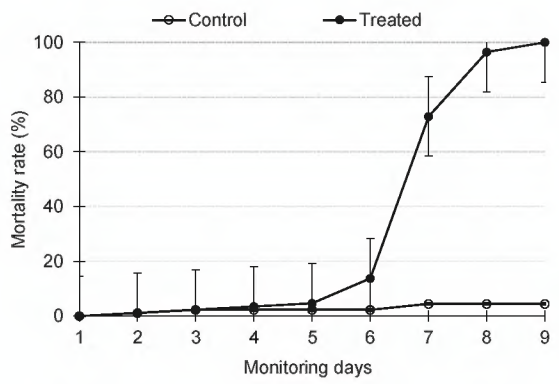

Fig. 1. The mortality rate (mean) of desert locust nymphs treated with a diluted solution of the powder formulation of *Metarhizium acridum* at the reception of the biopesticide. Error bars represent the standard error of the mean. Spore concentration in the used solution was 5×10^7 spores/mL (dilution factor of 1:1000), representing 5×10^4 spores/insect with an applied volume of 1 µL /locust

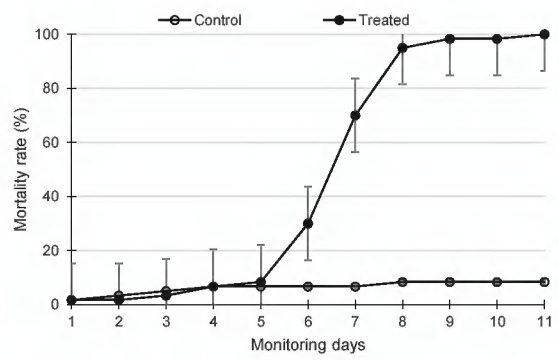

Fig. 2. The mortality rate (mean) of desert locust nymphs treated with a diluted solution of the powder formulation of *Metarhizium acridum* after 5 years of storage in a refrigerator at 4 °C. Error bars represent the standard error of the mean. Spore concentration in the used solution was 5×10^7 spores/mL (dilution factor of 1:1000) representing 5×10^4 spores/insect with an applied volume of 1 µL/locust

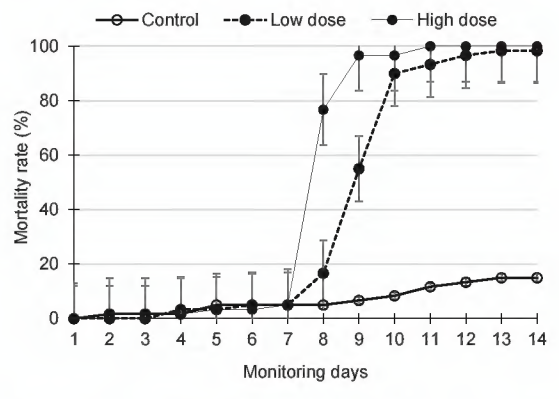

Fig. 3. The mortality rate (mean) of desert locust nymphs treated with a diluted solution of the powder formulation of *Metarhizium acridum* after 10 years of storage in a refrigerator at 4 ° C. Error bars represent the standard error of the mean. Spore concentration in the used solution was 5×10^7 spores/mL (dilution factor of 1:1000) representing 5×10^4 spores/insect and 5×10^4 spores/mL (dilution factor of 1:1000000) representing 5×10^1 spores/insect for high and low doses, respectively

Field efficacy of the formulation.—Measurements of plant size and cover revealed significant differences (Mann-Whitney U = 200.5; $P < 0.001$) between Plots A and B (Figs 4, 5). Plot A was characterized by large, widely dispersed plants, and Plot B consisted of smaller, closely spaced plants (Fig. 6A–C).

The quantity used for the field trial had been stored for three years beyond the expiry date indicated on the packaging. The results showed good efficacy of the biopesticide formulation under field conditions after this period. Meteorological conditions were considered suitable for the efficacy of *M. acridum*. Temperature ranged from 9 to 36 °C (mean ± SD: 21.07 ± 5.08 °C). Relative humidity varied between 12% and 64% (mean ± SD: 36 ± 7.19%).

Two weeks after the biopesticide application, locust populations in the treated zone were clearly reduced compared with those in the untreated zone. In contrast, in the untreated zone, most nymphs had become 5th instar, winged adults, forming cohesive and active bands. The results found in the field were confirmed by the mortality of caged nymphs collected from the field two days after biopesticide application (Fig. 7).

The results show no effect of plant size or cover on the efficacy of biopesticides applied under field conditions. For the locusts collected from the field on the second day and reared in cages, mortality 14 days later was 82.8% in Plot A and 83.9% in Plot B, whereas mortality in the Control was only 4.3%, without any fungal symptoms in the dead nymphs (F value = 81.112; df = 2, 6; $p < 0.001$). Post-hoc analysis using the Student–Newman–Keuls (SNK) test confirmed no significant difference in mortality rate between the caged locusts taken from Plot A and those taken from Plot B ($p = 0.962$). These results show that the biopesticide was effective for biotopes characterized by large and dispersed plants, as well as those characterized by small and closely spaced plants.

In general, the first signs of infection by the fungus appeared after one week of locust monitoring. Even though the first mortality in the cages was a day later in locusts taken from Plot B (Fig. 7),

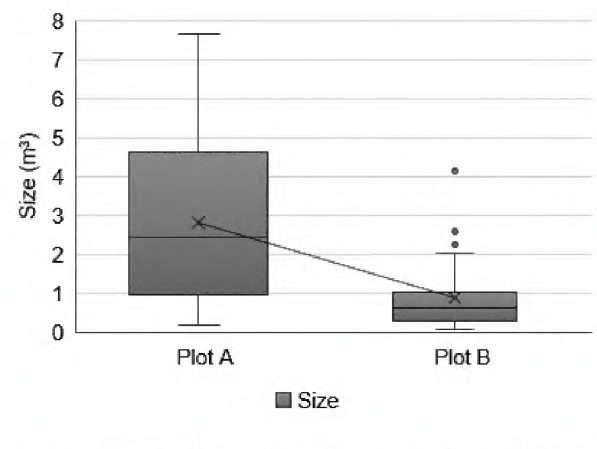

Fig. 4. Box plot showing the size (length × width × height) of the dominant plant of *Schouwia thebaica* in Plots A (N = 30) and B (N = 38) randomly selected as samples in different parts of the plot

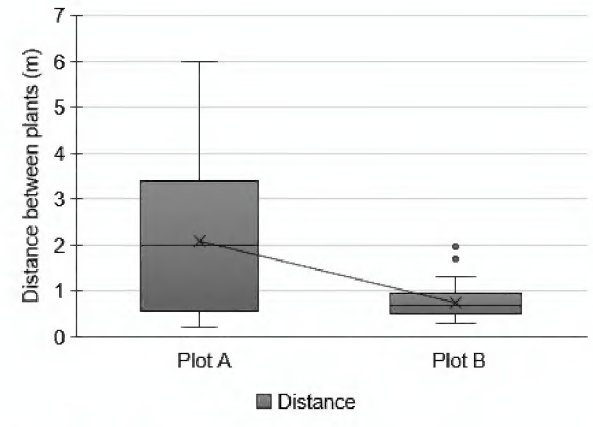

Fig. 5. Box plot showing the distance between dominant plants of *Schouwia thebaica* in plots A (N = 30) and B (N = 38) randomly selected as samples in different parts of the plot

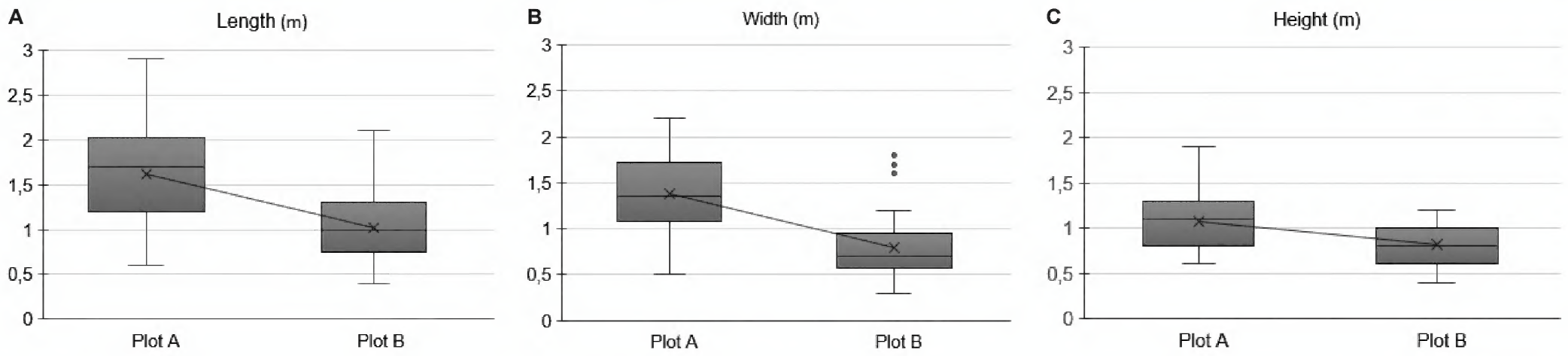

Fig. 6. Box plot measurements conducted in Plots A (N = 30) and B (N = 38) for plant dimensions (m), **A.** Length (L), **B.** Width (W) and **C.** Height (H) of *Schouwia thebaica* plants randomly sampled from different parts of the plot.

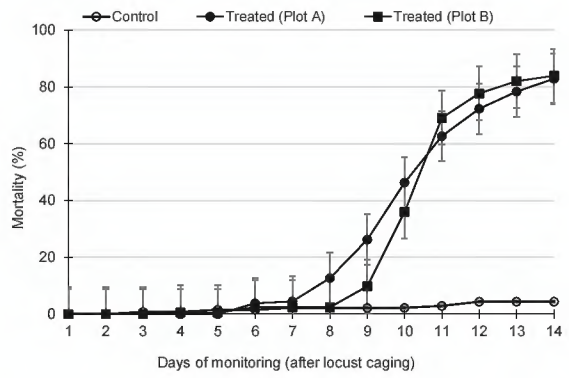

Fig. 7. The daily mortality rate of caged nymphs taken from Plots A and B two days after field applications of *Metarhizium acridum* that had been stored for three years. Error bars represent the standard error of the mean

the Student-Newman-Keuls (SNK) test showed that by day 10 the mortality of locusts taken from Plot A was similar to that for locusts taken from Plot B ($p = 0.793$). On day 10, the mortality rate of the caged locusts was 2.16%, 46.3%, and 36% for the Control, Plot A, and Plot B, respectively ($F = 21.28$; $df = 2.5$; $p = 0.004$). Two days later (day 12), mortality was 4.3% for the Control, 72.3% for Plot A, and 77.7% for Plot B ($F = 60.67$; $df = 2.5$; $p < 0.001$).

Discussion

This study demonstrates the remarkable long-term stability and field efficacy of biopesticide *M. acridum* for desert locust control. Spore viability remained above 90% for 10 years when stored under refrigeration at 4°C, with no detectable reduction in germination rate or virulence compared with the initial formulation. Even after temporary storage under ambient conditions, transport without refrigeration, and operational use in the field, spore viability was maintained. These findings provide strong evidence for the robustness of *M. acridum* formulations under both laboratory and operational conditions. The maintenance of virulence throughout the 10-year monitoring period is particularly noteworthy. Laboratory bioassays confirmed that spores stored for a decade were still capable of inducing high mortality in desert locusts at standard doses. This long-term stability exceeds the commonly recommended storage limits for biopesticides (Kooyman 2010) and suggests that properly stored formulations can remain effective well beyond their labeled expiry dates. Such stability is critical for operational programs, especially in regions where campaigns are irregular and the stockpiling of control agents is necessary. Field trials further confirmed the reliability of the stored formulation. Applications with product stored for three years beyond its expiry date achieved > 80% mortality of nymph populations within two weeks. These results are consistent with previous field evaluations of *M. acridum* (FAO 2004, Van der Valk 2007, Mullié et al. 2023), which reported high efficacy against nymph bands under operational conditions. Importantly, mortality was high in both experimental plots, despite pronounced differences in vegetation structure.

Plant size and cover did not significantly affect efficacy after 14 days, which suggests that *M. acridum* can perform reliably across a range of vegetation conditions encountered in desert locust habitats. The cage bioassays supported these findings, with mortality exceeding 80% in both treated plots and only 4.3% in the control. The absence of fungal symptoms in the control insects further confirmed the effectiveness of the treatments. Together, these results reinforce the potential of *M. acridum* as a dependable component of preventive locust management strategies, effective under varied field conditions and robust to logistical challenges in storage and transport.

Based on previous observations in the field, the optimum temperature for fungal growth was in the range of 27–30°C, with the most rapid growth occurring in the temperature range of 25–32°C (Blanford and Klass 2004). In field conditions, the same authors suggest that periods with cool nights (< 20°C) and moderately warm days (< 35°C) represent moderately favorable conditions for biopesticide effectiveness. Temperatures recorded during the study period ranged from 9–36°C, which falls within this temperature range. Under these conditions, the fungus has—at a suitable temperature—sufficient time to act. Relative humidity exerted no significant influence on biopesticide efficacy when applied under field conditions (Blanford and Klass 2004, Van der Valk 2007). We found a notable mortality rate of 70% to 80% two weeks following biopesticide application. These results are consistent with those found for the Italian locust, *Calliptamus italicus* (Linnaeus, 1758) (Orthoptera; Acrididae), despite conditions that qualified as relatively hot (temperatures reaching 40°C during the day) in that study (Hunter et al. 2016).

Vegetation is known to influence the efficacy of *M. acridum* under field conditions (Van der Valk 2007, Atheimine et al. 2014). We investigated the effects of plant size and cover on the efficacy of *M. acridum* under field conditions. *Schouwia thebaica* dominated the intervention zone. This species is essential to desert locusts, as it provides them with food and shelter. This plant can cover over 90% of an area and can reach a height of up to 2 m (Duranton et al. 2012). Our results showed that the biopesticide was equally effective in habitats with large and dispersed plants as well as in those with small and closely spaced plants.

Prior studies have demonstrated the influence of vegetation, species, size, and distribution on nymph bands of the desert locust under field conditions (Culmsee 2002, Babah and Sword 2004, Maeno et al. 2013). Nymph bands perched on plants during the night, and this behavior increases insect contact with spores through contaminated vegetation, making locusts suitable targets for biopesticide control (Maeno et al. 2013).

In our field observations, nymph bands rapidly vacated the treated plots, often on the same day as the treatment. The high mortality observed suggests that the threshold dose of spores required to cause infection was quickly reached, either through direct deposition or via contact with contaminated vegetation. As nymphs move through treated plants, they are more likely to accumulate lethal spore doses. Gregarious desert locusts typically form marching bands and use a variety of plant species as shelter (Culmsee 2002, Maeno et al. 2013).

At times, fungal spores can remain viable on vegetation for several months (Guerrero-Guerra et al. 2013). However, the residual activity of spores in the field remains unclear, and improving the persistence of *M. acridum* is one of the main challenges for its wider use (Aw and Hue 2017).

In conclusion, the systematic implementation of *M. acridum* in desert locust management remains challenging (Word Ries et al. 2024). A major obstacle continues to be the perception that biopesticides are less effective than chemical insecticides in suppressing locust infestations (Peveling 2005). Our study provides evidence of the operational use of *M. acridum* during a desert locust control campaign, confirming its efficacy in reducing local outbreaks under field conditions. Future studies should focus on optimizing its operational use by identifying technical constraints and defining more precise profiles of the efficacy and persistence of *M. acridum* under diverse conditions.

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References

Atheimine MO, Bashir MO, Ely SO, Kane CMH, Mohamed SAO, Babah MAO, Benchekroun M (2014) Efficacy and persistence of Metarhizium acridum (Hypocreales: Clavicipitaceae) used against desert locust larvae, Schistocerca gregaria (Orthoptera: Acrididae), under different vegetation cover types. International Journal of Tropical Insect Science 34: 106–114. https://doi.org/10.1017/S1742758414000228

Aw KMS, Hue SM (2017) Mode of Infection of Metarhizium spp. Fungus and Their Potential as Biological Control Agents. Journal of Fungi 3: 30. https://doi.org/10.3390/jof3020030

Babah MAO, Sword GA (2004) Linking Locust Gregarization to Local Resource Distribution Patterns Across a Large Spatial Scale. Environmental Entomology 33: 1577–1583. https://doi.org/10.1603/0046-225X-33.6.1577

Blanford S, Klass J (2004) Review of environment effects on the performance of Metarhizium anisopliae var. acridum against locusts under field conditions. Report for the Emergency Prevention System for Transboundary Animal and Plant Pests and Diseases (EMPRES). Food and Agriculture Organization of the United Nations, Rome.

Culmsee H (2002) The habitat functions of vegetation in relation to the behaviour of the desert locust Schistocerca gregaria (Forskal) (Acrididae: Orthoptera) - a study in Mauritania (West Africa). Phytocoenologia 32: 645–664. https://doi.org/10.1127/0340-269X/2002/0032-0645

Duranton J-F, Foucart A, Gay P-E (2012) Florule des biotopes du Criquet pèlerin en Afrique de l'Ouest et du Nord-Ouest: à l'usage des prospecteurs de la lutte antiacridienne. FAO-CLCPRO CIRAD, Alger Alger Montpellier.

FAO (2001) Desert Locust Guidelines 2. Survey.

FAO (2004) Evaluation of field trials data on the efficacy and selectivity of inecticides on Locusts and Grasshopers. FAO, Rome. Report to FAO by the Pesticide Referee Group - Ninth meeting, 23 pp.

FAO (2021) Evaluation of Field Trials Data on the Efficacy and Selectivity of Insecticides on Locusts and Grasshoppers.

FAO (2024) FAQs. Food and Agriculture Organization of the United Nations. http://www.fao.org/locusts/faqs/en/ [September 28, 2024]

Guerrero-Guerra C, Reyes-Montes M del R, Toriello C, Hernández-Velázquez V, Santiago-López I, Mora-Palomino L, Calderón-Segura ME, Fernández SD, Calderón-Ezquerro C (2013) Study of the persistence and viability of Metarhizium acridum in Mexico's agricultural area. Aerobiologia 29: 249–261. https://doi.org/10.1007/s10453-012-9277-8

Hunter DM, Latchininsky AV, Abashidze E, Gapparov FA, Nurzhanov AA, Medetov MZ, Tufliev NX (2016) The Efficacy of *Metarhizium acridum* Against Nymphs of the Italian Locust, *Calliptamus italicus* (L.) (Orthoptera: Acrididae) in Uzbekistan and Georgia. Journal of Orthoptera Research 25: 61–65. https://doi.org/10.1665/034.025.0204

Kooyman C (2010) L'entomopathogène Metarhizium acridum : une solution alternative à la lutte chimique contre les acridiens ravageurs.

Lomer CJ, Bateman RP, Johnson DL, Langewald J, Thomas M (2001) Biological Control of Locusts and Grasshoppers. Annual Review of Entomology 46: 667–702. https://doi.org/10.1146/annurev.ento.46.1.667

Lutte Biologique contre les Locustes et les Saute´riaux (LUBILOSA) (1999) Green Musclew User Handbook Version 4. Text: J. Langewald. LUBILOSA.

Maeno KO, Piou C, Ould Ely S, Babah MAO, Pélissié B, Ould Mohamed S, Jaavar MEH, Etheimine M, Nakamura S (2013) Plant Size-dependent Escaping Behavior of Gregarious Nymphs of the Desert Locust, Schistocerca gregaria. Journal of Insect Behavior 26: 623–633. https://doi.org/10.1007/s10905-013-9378-4

Mullié WC, Prakash A, Müller A, Lazutkaite E (2023) Insecticide Use against Desert Locust in the Horn of Africa 2019–2021 Reveals a Pressing Need for Change. Agronomy 13: 819. https://doi.org/10.3390/agronomy13030819

Ould Etheimine M, Kane CMH, Ould Ely S, Barry A, Mohamed SO, Babah MAO, Benchekroun M (2013) Storability of five new formulations of Green Muscle® (Metarhizium acridum) under ambient and low temperatures: evaluation of conidial viability and virulence against desert locust nymphs. International Journal of Tropical Insect Science 33: 195–201. https://doi.org/10.1017/S1742758413000131

Ould Maeno K, Piou C, Ould Ely S, Ould Mohamed S, El Hacen Jaavar M, Abdallahi Ould Babah M, Nakamura S (2012) Field Observations of the Sheltering Behavior of the Solitarious Phase of the Desert Locust, Schistocerca gregaria, with Particular Reference to Antipredator Strategies. Japan Agricultural Research Quarterly: JARQ 46: 339–345. https://doi.org/10.6090/jarq.46.339

Owuor A, David McRae H (2022) The Control of the Desert Locusts (*Schistocerca Gregaria*) in Somalia During the Upsurge Between 2019 and 2021. Outlooks on Pest Management 33: 221–226. https://doi.org/10.1564/v33_dec_02

Peveling R (2005) We believe what we see—and vice versa: evidence versus perception in locust control. Journal of Orthoptera Research 14: 207–212. https://doi.org/10.1665/1082-6467(2005)14[207:WBWWSV]2.0.CO;2

Van der Valk H (2007) Review of the efficacy of Metarhizium anisopliae var. acridum against the desert locust. Desert Locust Technical Series. AGP/DL/TS 34.

Word Ries M, Adriaansen C, Aldobai S, Berry K, Bal AB, Catenaccio MC, Cigliano MM, Cullen DA, Deveson T, Diongue A, Foquet B, Hadrich J, Hunter D, Johnson DL, Pablo Karnatz J, Lange CE, Lawton D, Lazar M, Latchininsky AV, Lecoq M, Le Gall M, Lockwood J, Manneh B, Overson R, Peterson BF, Piou C, Poot-Pech MA, Robinson BE, Rogers SM, Song H, Springate S, Therville C, Trumper E, Waters C, Woller DA, Youngblood JP, Zhang L, Cease A (2024) Global perspectives and transdisciplinary opportunities for locust and grasshopper pest management and research. Journal of Orthoptera Research 33: 169–216. https://doi.org/10.3897/jor.33.112803

Yasin M, Khan A, Qayyum MA, Yousuf HMB, Mehfooz A, Hunter D (2024) Biological control of locusts and grasshoppers: A review. Journal of Orthoptera Research 33: 289–304. https://doi.org/10.3897/jor.33.114472